An Integrated Positioning System

GPS + INS + Pseudolites

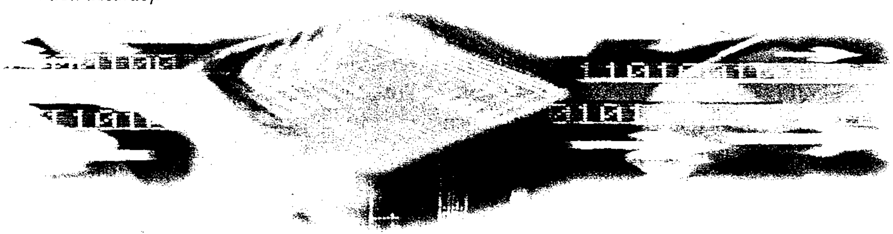
Yudan Yi, Dorota Grejner-Brzezinska, Charles Toth, Jinling Wang, and Chris Rizos

Kinematic positioning has become a standard GPS technique for precision navigation that supports surveying and mapping systems. One application for which the high accuracy and reliability of kinematic positioning are required is mobile mapping, whose market has significantly expanded in the past 10 years.

Inertial navigation systems (INSs) normally augment GPS to provide continuous and accurate trajectory and attitude information from the imaging sensors of mobile mapping systems. GPS contributes high accuracy and long-term stability (with properly resolved integer ambiguities and no losses of lock) and provides a means of error estimation for the INS sensor. A GPS-calibrated INS provides reliable bridging during GPS outages and supports ambiguity resolution after the GPS signal lock is reestablished. Thus, high navigation accuracy normally can be achieved even if GPS signals are subject to occasional blockages.

But what if GPS signals are lost for extended periods of time or the visible constellation is limited to four or fewer satellites, which can often happen in urban canyons? Pseudosatellites (pseudolites) may be the answer.

This month's column discusses an experimental GPS/INS/pseudolite system, with special emphasis on the error spectrum and the navigation performance analysis based on a medium-accuracy and highly reliable INS, limited GPS constellation availability, and a varying number of pseudolites. It also describes simulated and actual pseudolite data in typical noisy environments and analyzes their impact on navigation accuracy.



An integrated GPS/INS system constitutes a primary positioning component that supports direct platform orientation in mobile mapping systems. This configuration combines the advantages of high short-term accuracy and sampling rate of INS and high long-term accuracy and stability of GPS. To maintain sufficient accuracy and calibrate inertial sensor errors, however, at least four GPS satellites must be simultaneously observed (after the integer ambiguities have been resolved). This requirement holds for the so-called loose-integration scheme; the tight integration system can use fewer satellites. (In the tightly integrated approach, raw GPS observations update the GPS/INS filter, whereas a loosely coupled approach uses GPS-derived position and velocity updates that are combined with INS solutions in the GPS/INS filter.) However, none of the the integration modes can tolerate partial or complete losses of lock for very long.

Because without GPS calibration INS errors grow with time, the quality of the navigation solution decreases when the number of GPS satellites drops to fewer than four. In this case, stand-alone INS performs the navigation when loose coupling is used. Or, when tight integration is applied, only partial GPS information can be exploited (still, the filter observability is not equivalent to the case of four or more satellites required to estimate three-dimensional positions; for example, with three satellite observables only two coordinates can be determined). These circumstances create a significant drawback for land-based GPS/INS systems operating in urban canyons or open-pit mines where losses or partial blockages of GPS signals occur frequently. To circumvent this problem, one should use additional sensors such as pseudolites to augment the GPS/INS configuration.

What Are Pseudolites?

Pseudolites (PLs) are ground-based satellite-like transmitters that can generate and transmit GPS-like ranging signals to improve outdoor GPS availability or even entirely replace the GPS constellation for indoor applications. PLs transmit GPS-like signals on the L1 (1575.42 MHz) and possibly on L2 (1227.6 MHz) frequencies, using either the C/A-code or both C/A- and P-code. Normally, standard GPS receivers with minor firmware modifications can track PL signals. Introducing PL arrays can significanly improve satellite geometry. Consequently, positioning accuracy and reliability (both internal and external) can improve, especially in the vertical component and mainly as the result of the low elevation angle of PLs (normally less than 15 degrees).

PL signals may also support integer ambiguity resolution. The geometric configuration of PLs is very important, however, and becomes crucial for indoor applications. Even though PLs generally improve positioning accuracy, users should be aware of their negative aspects. For example, a much shorter distance exists between a PL and the user receiver than with a GPS satellite, so any errors in PL location will have a significant effect on the determined receiver antenna coordinates. The degree of influence depends on the geometry between the PLs and the receiver (weak geometry may even cause a singularity in the solution).

Another problem arises when a PL signal has a strong multipath signature, which may come not only from reflecting objects in the vicinity of a GPS receiver's antenna but also from the transmitter itself. In addition, the mixed differential technique (i.e., GPS and PL combined) compared with regular differential GPS (DGPS) might eliminate fewer error sources because of totally different geometry. As well, the PL signal could interfere with the satellite signals because the PL transmitter is very close to the receiving antenna, in contrast to the GPS satellites' position (the so-called *near–far problem*). Thus, the power level of the PL should be carefully controlled.

Typical applications of PLs are indoor/outdoor local positioning systems, personnel tracking systems, mobile object tracking and control systems in large factories, aircraft precision landing systems such as the Local Area Augmentation System, precision harbor entry, precision farming, heavy industry control in dangerous areas, military and special applications, and DGPS data links.

In the near future integrated INS, Global Navigation Satellite System, and PL technologies most likely will gain great flexibility and provide robust performance in a wide variety of difficult operational environments.

An Integrated System

Our GPS/INS/PL positioning system is based primarily on the original Airborne Integrated Mapping System (AIMS) concept developed at The Ohio State University in 1997, and its functionality has been expanded to accept PL observations. Integrating PL measurements into a GPS/INS system is relatively straightforward. A PL can be simply considered an additional GPS signal source that requires different weights and tropospheric model and has no ionospheric delay included in the observation equation, unlike GPS observables. Figure 1 illustrates the structure of the extended GPS/INS/PL integrated system. The system includes at least two GPS/PL receivers — the base and the rover — that track both GPS and PL signals. It also includes a medium-accuracy and highly reliable strap-down INS that provides attitude and velocity-rate measurements. (A strap-down INS does not use gimbals to stabilize its measurements. The inertial sensors remain in a fixed orientation with respect to the platform, and stabilization is performed computationally.) An extended Kalman filter provides a tightly coupled implementation that uses double-differenced (DD) carrier-phase measurements to optimally estimate position, velocity, and attitude of the platform. In addition, the accelerometer and gyroscope errors as well as gravity deflections and anomaly are also estimated.

Data Processing. The data postprocessing model of the extended GPS/INS/PL integrated system consists of three main steps:

- forming GPS/PL DDs
- strap-down navigation computation (i.e., the prediction step, using inertial measurements and sensor error estimates)
- GPS/INS/PL estimation (measurement update).

DD measurements between GPS satellites, PLs, and GPS receivers are formed to remove most of the systematic errors such as transmitter and receiver-clock

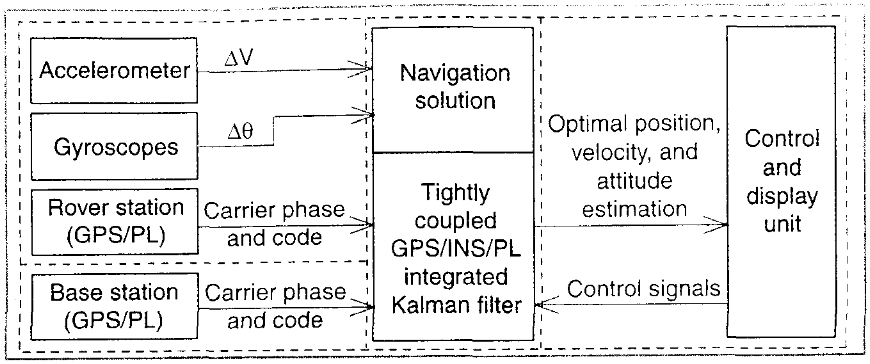


FIGURE 1 The design architecture of a GPS/INS/PL integrated system.

errors. Due to the low-elevation angle of PLs, an alternative tropospheric delay correction model has been implemented for PL data:

$$\Delta\delta_{tropo} = (77.6\,\frac{P}{T} + 375000\,\frac{e}{T^2})10^{-6}\Delta\rho$$

in which $\Delta\delta_{tropo}$ denotes the tropospheric correction between two receivers, $\Delta\rho$ is the difference in ranges between the PL and the base and the rover receivers, and P, T, and e are pressure in millibars, temperature in kelvins, and partial water-vapor pressure in millibars, respectively. Using "standard" tropospheric conditions at sea level (1013.25 millibars, 291.2 kelvins, and 15 millibars for pressure, temperature, and water vapor pressure, respectively), the tropospheric correction reaches 33.63 centimeters per kilometer of receiver spacing. The actual conditions may vary significantly from the standard atmosphere, however. For example, a deviation by +10 percent (−10 percent) from the standard conditions results in 33.03 centimeters per kilometer (34.37 centimeters per kilometer) tropospheric correction, and a +30 percent (–30 percent) deviation results in a 32.10 centimeters per kilometer (36.50 centimeters per kilometer) correction. Notice that there is no elevation-angle dependence in this model, and the assumption is that the meteorological conditions are identical for both receivers.

Real and Simulated Data

To investigate the performance of the GPS/INS/PL integrated system, we collected an experimental GPS/INS/PL dataset on May 4, 2001, at The Ohio State University campus. We selected a tall building (Lincoln Tower, whose height is 75 meters) as the location of a PL, which resulted in received signal elevation angles of 7 to 13 degrees depending on the vehicle location. Figure 2 shows the PL we used in our tests. We determined the precise coordinates of the transmitting antenna using GPS before the experiment. We placed the GPS antenna on the tripod and determined the precise coordinates of the phase center. Then we replaced the receiving antenna with a transmitting patch antenna and used the known separations of the phase centers of both antennas from the top of the tripod to compute the coordinates of the transmitting antenna phase center. We used two GPS receivers capable of tracking PL signals as base and rover stations. We installed an INS sensor, with a sampling rate of 256 hertz, in a vehicle together with the rover GPS receiver. During the test, we observed seven to eight GPS satellites for a total of approximately 4000 epochs at 1-hertz data rate.

Because only one PL was available, we simulated five additional PL datasets using predefined PL–rover–base geometry and applied random noise at the level displayed by a real PL measurement. Figure 3 shows the ground track of the GPS/INS/PL experiment and the locations of the PLs. Because the location of PLs has a significant effect on the solution quality, we selected the simulated PLs (PL2 to PL6) together with the real one

FIGURE 2 Pseudolite with transmitting antenna. We used a different antenna for our tests.

(PL1) to form a strong geometry that entirely enclosed the van trajectory.

Given that the PLs were assumed to be located at approximately 75 meters above the ground, the elevation angles relative to the rover station varied from approximately 7 to approximately 13 degrees, depending on the location of the roving receiver. During the experiment, eight GPS satellites were available above the elevation mask angle of 15 degrees, with elevation angles of 17, 20, 30, 40, 48, 50, 63, and 69 degrees (PRN26 at 69 degrees was selected as the base satellite for the double-differencing procedure). The mean of the DD a priori residuals for the real PL (PL1) was 0.14 millimeters, indicating no significant PL multipath bias in the signal. Figure 4 illustrates a base–PL–rover separation and corresponding PL elevation angle.

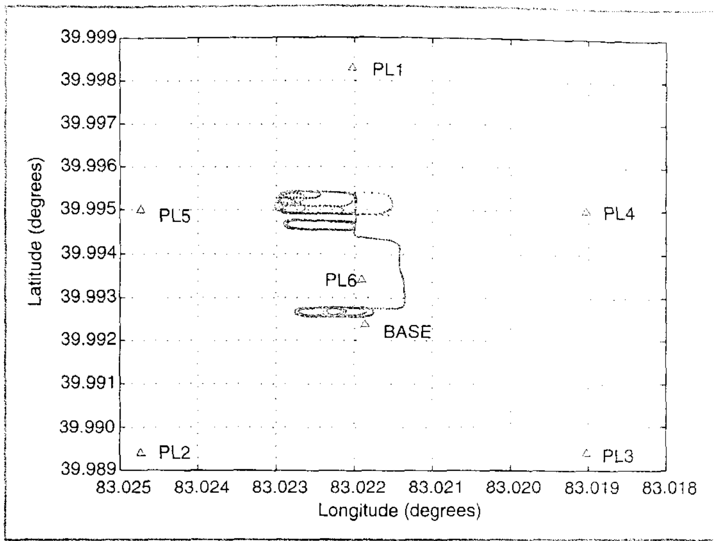


FIGURE 3 Ground track of the GPS/INS/PL experiment.

PL Effects

To assess the effects of using PLs on positioning accuracy, we obtained a reference ("true") solution using GPS/INS data only, with a constellation of seven to eight satellites that provided approximately 1-centimeter horizontal and approximately 2-centimeter vertical accuracy (one sigma). We compared this solution with other solutions that included the PL data from a varying number of PLs.

This article presents and analyzes the following solutions:

- all GPS satellites and one PL (GPS/INS/PL1)
- all GPS satellites and three PLs (GPS/INS/PL3)
- a solution based on four highest satellites and three PLs (GPS4/INS/PL3)
- a solution based on all available satellites and six PLs (GPS/INS/PL6).

Before the lower satellites were removed, 400 seconds of full GPS constellation data were used to calibrate INS errors.

Relative dilution of precision (RDOP) and relative vertical dilution of precision (RVDOP) are two important factors for evaluating the performance of DGPS. RDOP is a geometric factor that, similarly to DOP, is used to assess the geometrical strength of the actual satellite configuration, but for relative observations. The RDOP values can be computed prior to the survey, for analysis purposes, as a square root of the trace of the least squares cofactor matrix,

$$(A^T \Sigma^{-1} A)^{-1}/\sigma_\Phi^2,$$

in which Σ is theDD covariance matrix with σ_Φ^2 in the main diagonal. Figure 5 shows that the PL effects can be easily validated by comparing the RDOP and RVDOP with or without PLs. One can easily achieve significant improvements in RDOP and RVDOP by using more PLs in optimally selected locations.

A more interesting analysis can be performed by comparing RDOP and RVDOP of the GPS/INS/PL3 and the GPS4/INS/PL3 solutions with another one in which only the four highest satellites were used (GPS4/INS). The last (GPS4/INS) scenario simulates the urban canyon environment, where usually only the highest satellites can be tracked. Figure 6 clearly indicates that three low PLs combined with four high GPS satellites can bring RDOP and RVDOP back to the original level, achieved with seven to eight GPS satellites and three additional PLs.

Tables 1, 2, and 3 present a comparison of the reference solution (1) with GPS/INS/PL1 (2), and GPS4/INS/PL3 (3) and GPS/INS/PL6 (4) with GPS4/INS (5). Table 1 summarizes the root-mean-square (rms) differences in position, velocity,

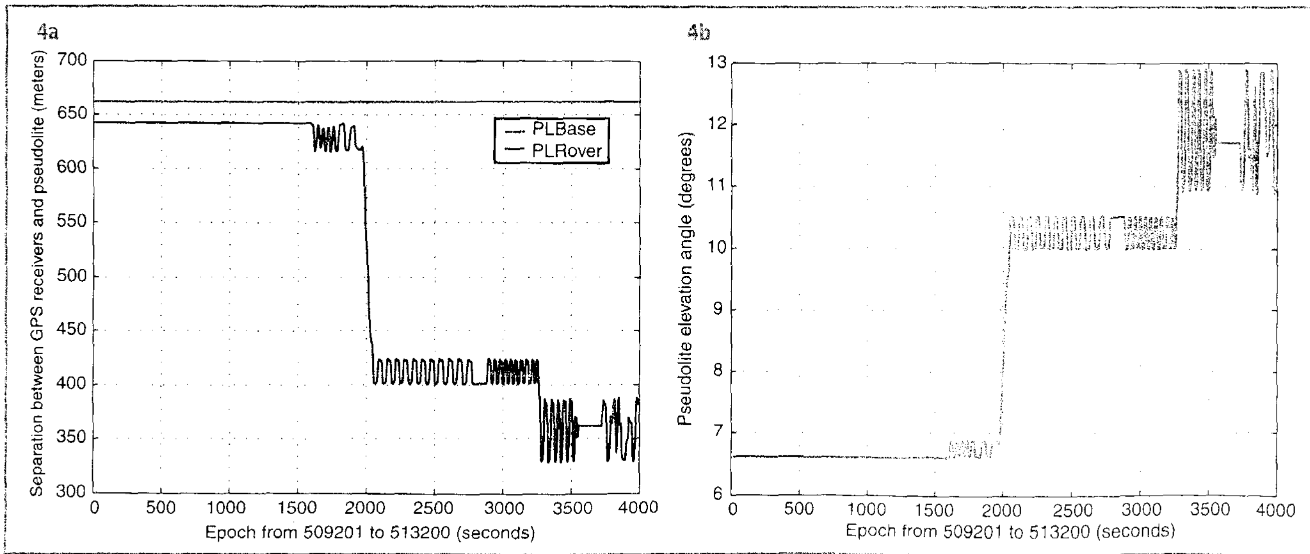


FIGURE 4 The base–PL and PL–rover separation (a) and the corresponding PL elevation angle from the rover (b).

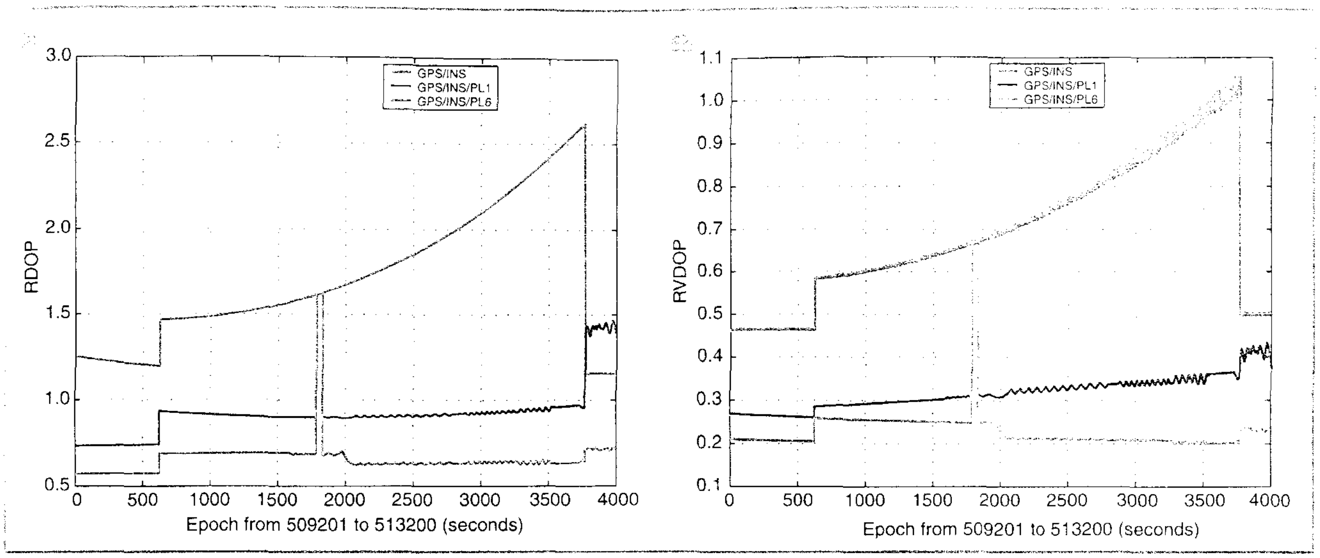


FIGURE 5 RDOP (a) and RVDOP (b) as a function of a number of PLs used.

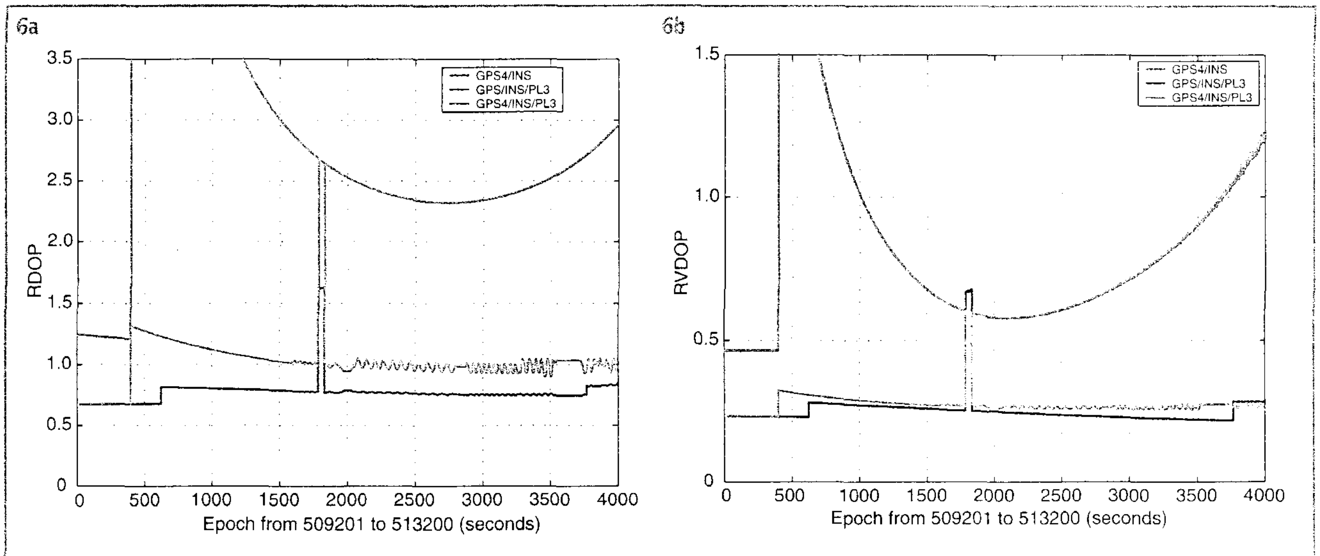


FIGURE 6 RDOP (a) and RVDOP (b) as a function of varying number of PLs and GPS satellites.

and attitude obtained from solutions (1) and (2), showing a very small effect on the positioning accuracy when one PL was added to the already geometrically strong constellation of seven to eight GPS satellites.

Tables 2 and 3 show the real impact of PLs on the positioning accuracy and indicate the differences in the rms between solutions (3) and (5), and (4) and (5). Clearly, the three PLs, replacing the missing GPS satellites, can significantly improve the rms. The use of six PLs further improves the quality, but not to a significant level because the solution with three PLs has already provided a very strong geometry. The most pronounced improvement is in the height component — approximately 2.5 centimeters. However, the horizontal rms also displays differences reaching approximately 1 centimeter, depending on the vehicle location and thus the effective geometry. Also, the vertical component of velocity and the heading are affected more than are the horizontal components of velocity and attitude (i.e, pitch and roll), respectively.

To better illustrate the effect of combining PL signals with INS observations during GPS signal blockages, Figure 7 shows the three-dimensional position errors as a function of the number of PLs used in the solution (INS was GPS calibrated for 2500 seconds before the GPS gap).

Ambiguity Resolution

A land-based GPS/INS system operating in urban environments is subject to frequent losses of GPS lock or partial obstructions that result in degradation of navigation accuracy. Consequently, limiting the extended partial or total signal blockages, as well as

TABLE 1 The mean, standard deviation (std), maximum, and minimum rms differences in position, velocity, and attitude between solutions (1) and (2).

Difference	Mean	Std	Max	Min	Units
rms_N	0.4	0.4	1.8	0.0	mm
rms_E	0.1	0.1	1.0	0.0	mm
rms_H	1.2	0.8	3.1	0.1	mm
rms_{Vn}	0.0	0.0	0.1	0.0	mm/s
rms_{Ve}	0.0	0.0	0.1	0.0	mm/s
rms_{Vd}	0.1	0.0	0.1	0.0	mm/s
$rms_{Heading}$	0.3	0.6	2.8	−0.3	arcsec
rms_{Pitch}	0.1	0.1	0.2	0.0	arcsec
rms_{Roll}	0.0	0.0	0.1	0.0	arcsec

TABLE 2 The mean, standard deviation (std), maximum, and minimum rms differences in position, velocity, and attitude between solutions (3) and (5).

Difference	Mean	Std	Max	Min	Units
rms_N	2.9	1.8	7.2	0.2	mm
rms_E	1.0	0.9	6.6	0.0	mm
rms_H	8.1	4.5	25.6	0.6	mm
rms_{Vn}	0.2	0.0	0.4	0.0	mm/s
rms_{Ve}	0.0	0.0	0.4	0.0	mm/s
rms_{Vd}	0.3	0.2	0.7	0.0	mm/s
$rms_{Heading}$	1.8	3.1	15.9	−0.4	arcsec
rms_{Pitch}	0.3	0.4	0.8	−0.0	arcsec
rms_{Roll}	0.1	0.2	0.5	0.0	arcsec

TABLE 3 The mean, standard deviation (std), maximum, and minimum rms differences in position, velocity, and attitude between solutions (4) and (5).

Difference	Mean	Std	Max	Min	Units
rms_N	3.4	2.0	8.1	0.2	mm
rms_E	2.1	1.7	10.1	0.0	mm
rms_H	9.4	4.6	25.7	0.6	mm
rms_{Vn}	0.2	0.1	0.6	0.0	mm/s
rms_{Ve}	0.1	0.1	0.6	0.0	mm/s
rms_{Vd}	0.3	0.2	0.7	0.0	mm/s
$rms_{Heading}$	2.5	4.2	21.9	−0.1	arcsec
rms_{Pitch}	0.4	0.4	1.0	0.0	arcsec
rms_{Roll}	0.2	0.2	0.6	0.0	arcsec

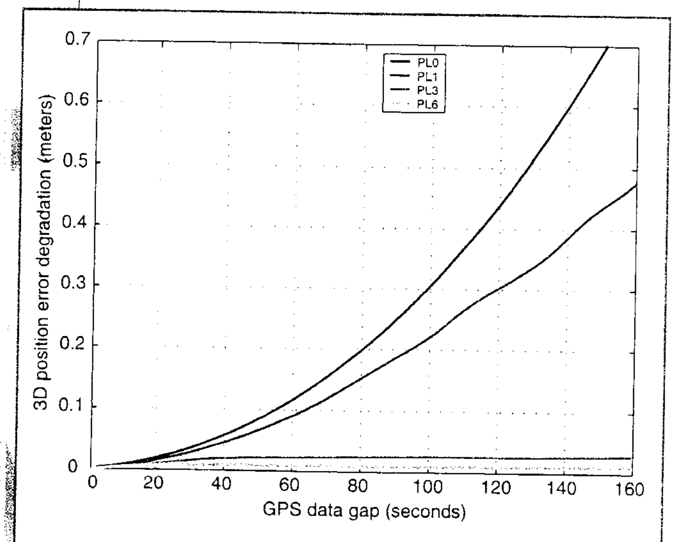


FIGURE 7 Three-dimensional position errors as a function of the number of pseudolites used in the solution (INS/PL).

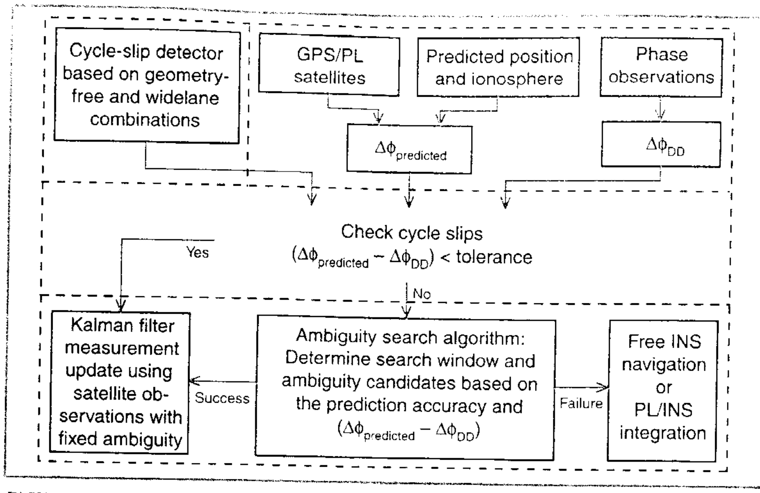


FIGURE 8 Pseudolite-supported ambiguity resolution scheme.

providing a fast means of recovery after the signal is reacquired, are very important characteristics of a well-designed system. Naturally, fast and reliable ambiguity resolution will play a crucial role in the navigation accuracy after GPS signal reacquisition.

The original GPS/INS integrated system, AIMS, developed at The Ohio State University, can provide fast and reliable detection of cycle slips and can fix ambiguities quickly after short losses of GPS lock (e.g., for a GPS gap of 30 seconds, 92–100 percent of ambiguities can be resolved within the first two epochs, if zero velocity update calibration is also performed; for 60-second gaps, 67–100 percent of ambiguities can be resolved within the first 20 epochs). However, the system may become less reliable in cases of frequent and extended losses of GPS lock, especially when base–rover separation exceeds a few tens of kilometers. This behavior occurs primarily because the ambiguity resolution algorithm (cycle-slip detection and fixing) is supported by the approximation from the INS predictor, which is accurate only for a relatively short time (up to approximately 60–80 seconds, depending on the quality of INS, the level of its calibration, and vehicle dynamics prior to the loss of lock).

Introducing a PL array augments the effective number of satellites when few GPS satellites are available and should present better and more-stable approximation for the ambiguity resolution module compared with that from the INS predictor only, which we will now demonstrate.

Figure 8 illustrates the primary principles of the PL-supported ambiguity resolution in the GPS/INS/PL system. First, we used the INS-predicted position and ionosphere information (for long baselines, ionospheric effects are estimated from dual-frequency carrier-phase data) from the previous epoch together with the GPS/PL coordinates to calculate the predicted DD carrier phases, and we formed the measured DDs. This step is based on the assumption that a minimum of four GPS satellites is available, and it still holds with the augmentation of PLs. The second step applies a cycle-slip detector based on geometry-free and wide-lane combinations that require both L1 and L2 data. If the PLs transmit both L1 and L2 signals, they could also be used in this step. However, the PLs we used transmitted only on L1.

The next step depends on the result of the first two steps; if the approximation is sufficiently good and no cycle slip exists, the fixed ambiguities (from the previous epoch) can be used directly in the Kalman filter GPS measurement update. Otherwise, the processor enters the ambiguity search loop.

In the search algorithm, the software estimates the ambiguity candidates from the INS/PL prediction and determines the search window according to the prediction accuracy. The search results depend on the accuracy of the ambiguity prediction and the width of the search window. The final step — GPS measurement update — follows if the ambiguities are successfully solved. Otherwise the system can use the PL data to update the filter if no cycle slips were detected on PL signals. The ambiguity resolution step is repeated on an epoch-by-epoch basis if the ambiguities cannot be fixed instantly.

To evaluate the performance of the PL-supported ambiguity resolution, we processed the GPS/INS/PL data combining the real and simulated PL signals. We introduced multiple gaps of 90 and 120 seconds into the GPS data, leaving only the reference satellite (in our current configuration no PL/PL DDs are formed). Thus, during a GPS gap, we used the INS/PL navigation mode. We obtained several solutions with a varying number of PLs (0, 1, 3, or 6); Table 4 compares the ambiguity resolution speed for these solutions. The number of PLs and the gap duration are the primary variables in Table 4.

Table 4 shows that during the first 5 seconds after a 90-second gap, 100 percent of the ambiguities were fixed with the presence of six PLs, while only approximately 76 percent can be fixed with the support from three PLs. Clearly, a good constellation of six PLs and the highest GPS satellite provided, together with INS data, a very good ambiguity prediction and allowed a quick validation, as compared with the case having only three PLs. Also, the GPS gap duration affects the speed of the ambiguity resolution after the GPS signal is reacquired. For different gaps and one PL or no PL solutions, however, the quality of the prediction is primarily a function of the INS quality. A more significant difference between the top and the bottom of Table 4, due to the increased number of PLs, can be observed for the case of three and six PLs.

To further illustrate the benefits of including PLs in the GPS ambiguity resolution procedure after a GPS signal blockage, Figure 9 compares the L1 minimum detectable bias (MDB) for solutions with all seven to eight satellites (GPS/INS), all GPS satellites and six PLs (GPS/INS/PL6), and four highest GPS satellites and six PLs (GPS4/INS/PL6). MDB is a measure of the internal reliability of the solution; i.e., the ability of the redundant observations to detect and identify specific model errors. In other words, it describes the size of model errors that can be detected by using the appropriate test statistics and can be

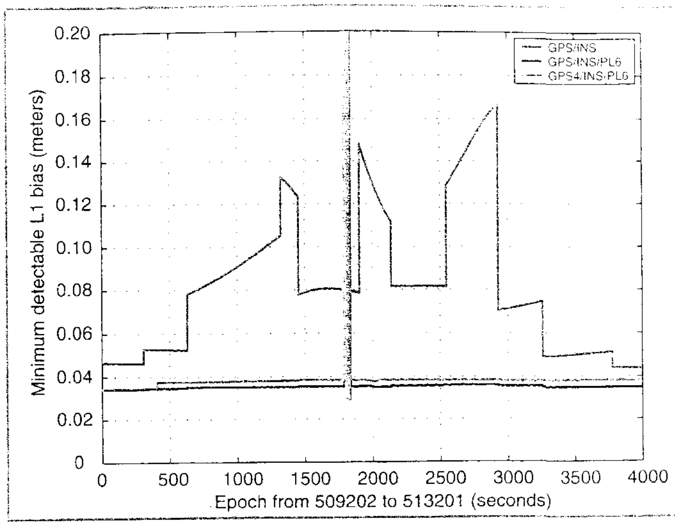


FIGURE 9 MDB comparison as a function of the number of PLs used (the spikes around epoch 1800 reflect the loss of PL signal).

Further Reading

For an introduction to pseudolites and their uses, see

- "Pseudolites: Enhancing GPS with Ground-Based Transmitters," by S. Cobb and M. O'Connor, *GPS World*, Vol. 9, No. 11, May 1998, pp. 55–60.

For information about The Ohio State University's Airborne Integrated Mapping System, see

- "High-Accuracy Airborne Integrated Mapping System," by D.A. Grejner-Brzezinska, in *Advances in Positioning and Reference Frames, the Proceedings of the International Association of Geodesy Scientific Assembly* (edited by F. Brunner), Rio de Janeiro, Brazil, 3–9 September 1997, pp. 337–342.
- "Direct Exterior Orientation of Airborne Imagery with GPS/INS System: Performance Analysis," by D.A. Grejner-Brzezinska, *Navigation*, Vol. 46, No. 4, 1999, pp. 261–270.

For further details about augmenting a GPS/INS system with pseudolites, see

- "Robust GPS/INS Integrated System in Urban Region: GPS/INS/Pseudolite Integration," by Y. Yi, in the *Proceedings of ION GPS 2002, the 15th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Portland, Oregon, September 24–27, 2002, pp. 2396–2405.
- "Experimental GPS/INS/Pseudolite System for Kinematic Positioning," by D.A. Grejner-Brzezinska and Y. Yi, *Survey Review*, Vol. 37, No. 288, 2002, pp. 113–126.
- "GPS/INS/Pseudolite Integration: Concepts, Simulation, and Testing," by J. Wang, L. Dai, T. Tsujii, C. Rizos, D.A. Grejner-Brzezinska, and C.K. Toth, in *Proceedings of ION GPS 2001, the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Salt Lake City, Utah, September 11–14, pp. 2707–2715.

TABLE 4 Pseudolite-supported ambiguity resolution speed based on 120-second gaps with 10 segments (top) and 90-second gaps with 13 segments (bottom).

Ambiguity fixing speed (s)	Percent of Fixed Ambiguities as a Function of Number of PLs			
	0	1	3	6
	After 120-s GPS Gap			
1–5	30	50	70	90
6–30	40	40	20	10
>30 unfixed	30	10	10	0
	After 90-s GPS Gap			
1–5	46	61	76	100
6–30	31	15	8	0
>30 unfixed	23	24	16	0

computed on the basis of the network configuration and the stochastic model (no observations are needed). Thus, MDBs can be computed in the design or planning stage of a survey or experiment and are important diagnostic tools to infer the strength with which positioning models can be validated. In general, a small MDB (e.g., below 0.5 cycle) indicates the system's capability of detecting the smallest cycle slips. Clearly, low PLs can replace the missing GPS satellites and create a very strong geometry and small MDB.

Summary and Conclusions

Our performance analysis of a GPS/INS/PL model based on the experimental and simulated data clearly indicates the advantages of using PLs in land-based mobile mapping and precision navigation. We demonstrated improvements in RDOP, RVDOP, and rms, especially in the vertical component of a GPS/INS/PL solution compared with a GPS/INS solution that included a limited number of GPS satellites. A practical example of on-the-fly ambiguity resolution with various numbers of PLs included indicated that use of PL arrays is very beneficial. Other issues such as multipath mitigation (especially in kinematic and indoor applications), the stochastic properties of PL observables, and the optimal locations of PLs and the possible presence of multipath bias in pseudolite signals, especially when patch antennas are used, are the subjects of further research.

Acknowledgments

This article is based on a paper presented at the Weikko A. Heiskanen Symposium in Geodesy held in Columbus, Ohio, October 1–5, 2002, to celebrate 50 years of teaching and researching geodetic science at The Ohio State University, and a paper presented at the Second Symposium on Geodesy for Geotechnical and Structural Engineering, held in Berlin, Germany, May 21–24, 2002.

Manufacturers

Our tests used an **IntegriNautics Corp.** (Menlo Park, California) *IN200 PL* with a **Rojone Pty. Ltd.** (Sydney, Australia) GPS 2000 antenna. The base and rover GPS receivers were **NovAtel Inc.** (Calgary, Alberta, Canada) *OEM MiLLenium RT2* receivers modified for PL compatibility. The inertial navigation unit in our system is a **Litton Industries Inc.** (now the **Navigation Systems Division of Northrop Grumman Corp.**, Los Angeles, California) *LN-100*.

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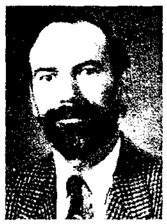
Dr. Jinling Wang *is a lecturer in the School of Surveying and Spatial Information Systems at the University of New South Wales (UNSW), Sydney, Australia. He is the chairman of the International Working Group on pseudolite applications within the International Association of Geodesy (IAG).*

Prof. Chris Rizos *is a graduate of UNSW, where he obtained a Bachelor of Surveying in 1975 and a Doctor of Philosophy in 1980 in satellite geodesy. He is currently leader of the Satellite Navigation and Positioning group at UNSW and president of IAG's Commission 4 "Positioning and Applications."*



"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 2 of this issue.